# OPTICAL COMMUNICATIONS USING HETERODYNE DETECTION

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## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

This invention relates generally to optical fiber communications, and more particularly, to the use of heterodyne detectors in receivers for optical fiber communications systems.

### 2. Description of the Related Art

As the result of continuous advances in technology, particularly in the area of networking, there is an increasing demand for communications bandwidth. For example, the growth of the Internet, home office usage, e-commerce and other broadband services is creating an ever-increasing demand for communications bandwidth. Upcoming widespread deployment of new bandwidth-intensive services, such as xDSL, will only further intensify this demand. Moreover, as data-intensive applications proliferate and data rates for local area networks increase, businesses will also demand higher speed connectivity to the wide area network (WAN) in order to support virtual private networks and high-speed Internet access. Enterprises that currently access the WAN through T1 circuits will require DS-3 and OC-3 connections in the near future. As a result, the networking infrastructure will be required to accommodate greatly increased traffic.

Optical fiber is a transmission medium that is well-suited to meet this increasing demand. Optical fiber has an inherent bandwidth which is much greater than metal-based conductors, such

as twisted pair or coaxial cable. There is a significant installed base of optical fibers and protocols such as the OC protocol have been developed for the transmission of data over optical fibers. The transmitter converts the data to be communicated into an optical form and transmits the resulting optical signal across the optical fiber to the receiver. The receiver recovers the original data from the received optical signal. Recent advances in transmitter and receiver technology have also resulted in improvements, such as increased bandwidth utilization, lower cost systems, and more reliable service.

However, current optical fiber systems also suffer from drawbacks which limit their performance and/or utility. For example, optical fibers typically exhibit dispersion, meaning that signals at different frequencies travel at different speeds along the fiber. More importantly, if a signal is made up of components at different frequencies, the components travel at different speeds along the fiber and will arrive at the receiver at different times and/or with different phase shifts. As a result, the components may not recombine correctly at the receiver, thus distorting or degrading the original signal. In fact, at certain frequencies, the dispersive effect may result in destructive interference at the receiver, thus effectively preventing the transmission of signals at these frequencies. Dispersion effects may be compensated by installing special devices along the fiber specifically for this purpose. However, the additional equipment results in additional cost and different compensators will be required for different types and lengths of fiber.

As another example, the transmitter in an optical fiber system typically includes an optical source, such as a laser, and an external modulator, such as a Mach-Zender modulator (MZM). The source generates an optical carrier and the modulator is used to modulate the optical carrier with the data to be communicated. In many applications, linear modulators are preferred in order to increase the performance of the overall system. MZMs, however, are inherently nonlinear devices. Linear operation is approximated by biasing the MZM at its quadrature point and then limiting operation of the MZM to a small range around the quadrature point, thus reducing the effect of the MZM's nonlinearities. However, this results in an optical

signal with a large carrier (which contains no information) and a small modulated signal (which contains the data to be communicated). A larger optical signal to noise ratio is required to compensate for the large carrier.

Thus, there is a need for optical communications systems which reduce or eliminate the deleterious effects caused by fiber dispersion. There is further a need for approaches which reduce the power contained in the optical carrier.

## SUMMARY OF THE INVENTION

In accordance with the present invention, a receiver is for recovering an information signal from an optical signal which includes at least one tone and at least one sideband of the information signal. The optical carrier for the optical signal may serve as the tone or the tone may be located at a different frequency. The receiver includes a heterodyne detector coupled to a signal extractor. The heterodyne detector mixes the optical signal with an optical local oscillator signal to produce an electrical signal which is a frequency down-shifted version of the optical signal. The signal extractor mixes one of the tones with one of the sidebands, generating a component, preferably a difference component, which contains the original information signal.

In one embodiment, the signal extractor includes two frequency filters and a square law device. The first frequency filter selects both the tone and the sideband from the electrical signal received from the heterodyne detector. The square law device squares the signal containing the tone and sideband, thus mixing the two. The second frequency filter selects the difference component generated in the mixing. In another embodiment, the signal extractor includes three frequency filters and a multiplier. Two of the frequency filters select the tone and sideband, respectively, from the electrical signal produced by the heterodyne detector. The multiplier multiplies the tone with the sideband, thus mixing them. The third frequency filter selects the resulting difference component.

In yet another embodiment, the optical signal includes two sidebands, for example an upper and a lower sideband. The signal extractor includes two extraction paths and a combiner. Each extraction path recovers a component from one of the sidebands, by mixing the applicable sideband with a tone. The two sidebands are then constructively combined by the combiner, for example by first phase-shifting them to be in-phase with each other. The resultant component contains the information signal.

The present invention has many advantages. For example, sidebands are processed separately from each other. This reduces the dispersion effects since the sidebands are prevented from destructively interfering with each other. The use of the difference component, rather than for example the sum component, results in the cancellation of phase noise which is common to both the sideband and the tone. As a final example, if a pilot tone is used, the optical carrier may be significantly reduced.

In further accordance with the invention, a method for recovering an information signal from the optical signal includes the following steps. The optical signal is received. An optical local oscillator signal is also received. The optical signal is detected using heterodyne detection and the optical local oscillator signal, resulting in an electrical signal which is a frequency down-shifted version of the optical signal. One of the sidebands is mixed with one of the tones to generate a component, preferably a difference component, containing the information signal.

## BRIEF DESCRIPTION OF THE DRAWING

The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a block diagram of a system 100 according to the present invention;

FIG. 2 is a flow diagram illustrating a method 200 for transmitting an information signal across a fiber, according to the present invention;

FIG. 3 is a diagram of one embodiment 310 of transmitter 110 using a Mach-Zender modulator;

FIG. 4 is a graph illustrating a transfer function 400 for MZM 314;

FIG. 5 is a diagram of another embodiment 510 of transmitter 110 using a three-armed modulator;

FIG. 6 is a block diagram of one embodiment 690 of signal extractor 190 based on squaring a signal containing a tone and a sideband;

FIG. 7 is a block diagram of another embodiment 790 of signal extractor 190 based on multiplying a tone with a sideband;

FIG. 8 is a block diagram of yet another embodiment 890 of signal extractor 190 using separate extraction paths to process different sidebands;

FIG. 9 is a block diagram of one embodiment 990 of signal extractor 890 based on multiplying a tone with a sideband; and

FIG. 10 is a diagram of another embodiment 1010 of transmitter 110 using pilot tones.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a diagram of a system 100 according to the present invention. System 100 includes a transmitter 110 coupled to a receiver 130 by optical fiber 120. The receiver 130 preferably includes a heterodyne detector 180 coupled to a signal extractor 190. System 100 is used to transmit an information signal from transmitter 110 to receiver 130 via fiber 120.

With reference to the flow diagram of FIG. 2 as well as to FIG. 1, system 100 operates as follows. The frequency spectrum of an exemplary information signal is shown by spectrum 140, which is characterized by a frequency $f_S$. The frequency $f_S$. could be zero, for example, if the information signal is based on on-off keying. The information signal 140 may be any of a variety of signals. For example, it may be a single high speed data stream. Alternately, it may contain a number of data streams which are time-division multiplexed together, for example, if 64 OC-3 data streams are combined together to form a single OC-192 signal, which serves as the information signal 140. As another example, the information signal may include a number of constituent signals, each of which occupies a different frequency band within spectrum 140. In other words, the constituent signals may be frequency division multiplexed together. Other types of information signals 140 and methods for combining constituent signals to form the information signal 140 will be apparent.

Transmitter 110 receives 210 the information signal 140 and generates 220 an optical signal 142. Optical signal 142 is characterized by a carrier frequency $f_C$ and includes at least one sideband 144 based on the information signal 140 and at least one tone 146, shown at a frequency $f_t$ in the following examples. Various techniques may be used to achieve this function. In a preferred embodiment, transmitter 110 includes an optical source 112 coupled to an optical modulator 114. Examples of optical sources include solid state lasers and semiconductor lasers. Example optical modulators 114 include Mach Zehnder modulators, electro-optic modulators, and electro-absorptive modulators. The optical source 112 produces an optical carrier at the carrier frequency $f_C$. The modulator 114 receives 210 the information signal 140 and modulates the optical carrier with the information signal 140 to generate 220 optical signal 142. In the example of FIG. 1, double sideband modulation is illustrated, resulting in two sidebands (upper sideband 144U and lower sideband 144L) which are centered about the carrier frequency $f_C$. Other types of modulation, such as single sideband modulation, could also be used. Continuing this example, the modulator 114 also produces a significant component at the carrier frequency $f_C$, which serves as a tone 146. Alternately, transmitter 110 may include an internally modulated

laser. In this case, the information signal 140 drives the laser, the output of which is the optical signal 142.

The optical signal 142 is transmitted 230 over fiber 120 to receiver 130. Current optical fibers have two spectral regions which are commonly used for communications: the 1.3 and 1.55 micron regions. At a wavelength of 1.3 micron, transmission of the optical signal is primarily limited by attenuation in the fiber 120; dispersion is less of a factor. Conversely, at a wavelength of 1.55 micron, the optical signal will experience more dispersion but less attenuation. Hence, the optical signal preferably has a wavelength either in the 1.3 micron region or the 1.55 micron region and, for long distance communications systems, the 1.55 micron region is generally preferred.

At receiver 130, heterodyne detector 180 receives 235 the incoming optical signal 142 and also receives 240 an optical local oscillator signal 134 at a frequency $f_{LO}$. In FIG. 1, the local oscillator signal 134 is shown at a frequency $f_{LO}$ which is lower than the carrier frequency $f_c$, but the local oscillator signal 134 may also be located at a frequency $f_{LO}$ which is higher than the carrier frequency $f_c$. Examples of optical local oscillators 132 include solid state lasers and semiconductor lasers. The optical signal 142 and local oscillator signal 134 are combined 245 and heterodyne detection 250 of the combined signal effectively downshifts the optical signal 142 from a carrier at frequency $f_c$ to a frequency $\Delta f$, which is the difference between the local oscillator frequency $f_{LO}$ and the carrier frequency $f_c$. The resulting electrical signal has spectrum 150. Note that both sidebands 154L and 154U, and tone 156 have also been frequency downshifted compared to optical signal 142. Signal extractor 190 then mixes 260 at least one of the sidebands 154 with one of the tones 156 to produce, among other things, a component 170 located at the difference frequency $\Delta f$ between the sideband 154 and tone 156. This difference component 170 contains the information signal 140, although it may be offset in frequency from $f_s$, depending on the frequencies of sideband 154 and tone 156. Components other than the difference component 170 may be used to recover the information signal. For example, the

mixing 260 typically also produces a sum component located at the sum frequency of sideband 154 and tone 156, and the information signal 140 may be recovered from this sum component rather than the difference component. If more than one sideband 154 is processed by signal extractor 190, each sideband 154 is processed separately from the others in a manner which prevents destructive interference between the sidebands.

However, recovering the information signal 140 based on the difference component of sideband 154 and tone 156 is advantageous because it results in noise cancellation. For example, sideband 154L and tone 156 are affected similarly by laser phase noise produced by optical source 112 and optical local oscillator 132. Using the difference component effectively subtracts the laser phase noise in sideband 154L from the laser phase noise in tone 156, resulting in significant cancellation of this noise source. In contrast, using the sum component would effectively reinforce the laser phase noise.

Processing the sidebands 154 separately from each other is also advantageous because it significantly reduces dispersion effects caused by fiber 120. For example, in direct detection receivers, upper and lower sidebands 154U and 154L would be processed together and, at certain frequencies for the sidebands 154 and lengths of fiber 120, the dispersion effects of fiber 120 would cause the two sidebands to destructively interfere, significantly impairing the recovery of information signal 140. By processing sidebands 154 separately from each other, signal extractor 190 avoids this deleterious dispersion effect.

In a preferred embodiment, heterodyne detector 180 includes a combiner 136 and a square law detector 137 coupled in series. Combiner 136 preferably is a fiber coupler, due to its low cost and applicability to fiber systems, although other types of combiners may be used. Square law detector 137 preferably is a PIN diode. Combiner 136 receives 235 the incoming optical signal 142 at one of its inputs and receives 240 the optical local oscillator signal 134 at the other input. Combiner 136 combines the local oscillator signal 134 with the optical signal 142 to produce the combined signal with spectrum 160. Heterodyne detector may also include a

polarization controller 139 coupled to the combiner 136 for matching the polarizations of the optical signal 142 and the local oscillator signal 134 so that the two signals are mixed efficiently at the square law detector 137. In FIG. 1, the polarization controller 139 is shown located between the local oscillator 132 and combiner 136 and controls the polarization of the local oscillator signal 134. Alternately, the polarization controller 139 may be located between the fiber 120 and combiner 136 and control the polarization of the optical signal 142. In another approach, polarization controller 139 may control the polarizations of both signals 134 and 142. Square law detector 137 produces a photocurrent which is proportional to the intensity of signal 160, which effectively mixes together the various components in spectrum 160. The resulting electrical signal has a number of components located at different frequencies, with the components of interest shown by spectrum 150. Spectrum 150 is similar to spectrum 142, but frequency downshifted from the carrier frequency $f_C$ to the difference frequency $\Delta f$.

FIGS. 3-9 are examples of various embodiments of signal extractor 190. These embodiments are illustrated using the example of FIG. 1 in which optical signal 142 includes two sidebands 144 and the optical carrier functions as a tone 146. The invention, however, is not limited to this specific example. Modulation schemes besides double sideband may be used (e.g., single sideband). Similarly, the tone 146 may be located at frequencies other than the carrier frequency $f_c$ and/or multiple tones 146 may be used.

FIG. 3 is a diagram of one embodiment 310 of transmitter 110, in which modulator 114 includes a Mach-Zender modulator (MZM) 314. MZM 314 includes two arms 316A and 316B, and an electrode 318 for receiving information signal 140. The optical carrier produced by source 112 is received by MZM 314, which splits it into two signals, one propagating through each arm 316. The information signal 140 applied to electrode 318 produces an electric field across each of the arms 316, causing a difference in the optical path through each arm 316 (e.g., due to the electro-optic effect). As a result of this difference in optical path, the optical signals propagating through the two arms 316A and 316B will either constructively or destructively

interfere when they are recombined at the output of the MZM 314. In other words, the output of MZM 314 depends on the relative phase difference between the two arms 316, which in turn depends on information signal 140.

FIG. 4 graphs the intensity of MZM 314 as a function of the relative phase shift between the two arms 316. Since MZM 314 is interferometric, the intensity of its optical output is a sinusoidal function of the relative phase shift between the two arms 316. For example, if the relative phase shift between the two arms 316 is a multiple of $2\pi$, then the signals in the two arms will constructively interfere, yielding a maximum intensity at the output as indicated by points 402A-402C. At the other extreme, two arms 316 which are out of phase will destructively interfere, yielding a minimum intensity at the output as shown by points 404A-404B, which shall be referred to as $V_\pi$ points. The interim cases result in the raised cosine transfer function 400 of FIG. 4. As described above, the relative phase shift is determined by the received information signal 140.

In one aspect of transmitter 310, the MZM 314 is biased at one of the quadrature points 406A-406D. At these quadrature points 406, the raised cosine transfer function may be used to approximates a linear transfer function, particularly if the modulator 314 is operated over a limited range around the quadrature points 406. When operated in this fashion, transmitter 310 results in the optical signal shown in spectrum 320. The raised cosine nature of transfer function 400 results in dual sidebands 324L and 324U; and operation at the quadrature point 406 results in a large component at the carrier frequency $f_c$, which may be used as a tone 326.

FIG. 5 is a diagram of another embodiment 510 of transmitter 110, in which the optical modulator 114 includes a three-armed modulator 514. Modulator 514 includes three arms 516A-516C. Two arms 516A-516B form a conventional MZM and information signal 140 modulates the signal in these two arms in the same manner as MZM 314 of FIG. 3. However, the MZM formed by arms 516A-516B is not biased at one of the quadrature points 406. Rather, it is operated at one of the $V_\pi$ points 404. The result is an optical signal which includes two

sidebands 524L and 524U but no optical carrier at $f_C$ since operation at the $V_\pi$ point 404 suppresses the carrier. The third arm 516C is used to reintroduce the optical carrier, preferably in a controlled manner by adjusting both the amplitude and phase of the carrier. For example, the amplitude and phase could be determined by adjusting the splitting ratios between the three arms 516 and/or the lengths of the arms 516, respectively. Alternately, control signal 530 could be used to adjust elements in arm 516C which control the amplitude and phase of the carrier in the arm. The reintroduced carrier then functions as a tone 526 in optical signal 520. This approach is advantageous compared to transmitter 314 because the amplitude and phase of optical carrier 526 may be tailored for different purposes. For example, since optical carriers 526 and 326 do not carry any information, the amplitude of carrier 526 may be minimized to reduce wasted power whereas the amplitude of carrier 326 is fixed by quadrature point 406.

A similar result may be obtained by various other approaches. For example, the third arm 516C may be replaced by an optical fiber. Some of the optical carrier produced by source 112 is diverted to the optical fiber and then recombined with the output produced by the MZM formed by arms 516A-516B. In another approach, the MZM formed by arms 516A-516B may be biased at a point other than the $V_\pi$ point 404, thus producing an optical carrier. However, the phase and/or amplitude of the unmodulated carrier in arm 516C may be adjusted so that it interferes with the carrier produced by arms 516A-516B to generate an optical carrier with a desirable amplitude. The net result is an optical carrier of reduced amplitude. Alternately, referring again to FIG. 3, MZM 314 may be biased at a point close to but slightly offset from the $V_\pi$ points 404. The slight offset will result in some carrier being introduced into the optical signal, thus resulting in a spectrum 330 with a reduced optical carrier as in spectrum 520.

FIG. 6 is a block diagram of one embodiment 690 of signal extractor 190 based on squaring a signal containing a tone and a sideband. Signal extractor 690 includes a bandpass filter 610, a square law device 620, and a low pass filter 630 coupled in series. The filters 610, 630 may be implemented in many different ways, for example, by a DSP chip or other logic

device implementing a digital filter, a lump LC filter, a surface acoustic wave filter, a crystal-based filter, a cavity filter, or a dielectric filter. Other implementations will be apparent. The square law device 620 also may be implemented in many different ways. A diode is one common implementation.

Signal extractor 690 recovers the information signal 140 from electrical signal 150 as follows. Bandpass filter 610 frequency filters one of the sidebands and one of the tones from electrical signal 150. In this example, signal 150 includes two sidebands 154 and an optical carrier 156. Bandpass filter 610 passes the upper sideband 154U and the optical carrier 156, and blocks the lower sideband 154L, thus producing spectrum 660. The square law device 620 squares the filtered components 660, resulting in spectrum 670. Spectrum 670 includes components 672 located at the difference of frequencies between sideband 154U and tone 156, and also components 674 located at the sum of these frequencies. Low pass filter 630 selects the difference components 672, thus recovering the information signal 140.

As noted previously, selection of the difference components 672 rather than the sum components 674 is advantageous because it effectively cancels any noise sources which are common to both the tone 156 and sideband 154. In addition, processing a single sideband 154U, rather than both sidebands 154U and 154L together, prevents any potential destructive interference between the sidebands, as may be caused by the frequency dispersion effects discussed previously.

FIG. 7 is a block diagram of another embodiment 790 of signal extractor 190 based on multiplying a tone with a sideband. This extractor 790 includes two bandpass filters 710 and 712, a multiplier 720 and a low pass filter 730. The two bandpass filters 710, 712 are each coupled to receive the incoming electrical signal 150 and are coupled on their outputs to multiplier 720. The multiplier is coupled to low pass filter 730.

Bandpass filter 710 selects a tone 156 and bandpass filter 712 selects one of the sidebands 154. In this specific example, the optical carrier and upper sideband 154U are the selected components. Multiplier 720 multiplies the tone 156 against the selected sideband 154U, resulting in a signal with a sum component 774 and a difference component 772, as in FIG. 6. Low pass filter 730 selects the difference component 772, thus recovering the information signal 140.

FIG. 8 is a block diagram of yet another embodiment 890 of signal extractor 190 using separate extraction paths for different sidebands. Example 890 includes two extraction paths 850A and 850B, and a combiner 860. Each extraction path 850 receives the incoming electrical signal 150 and is coupled on the output side to combiner 860.

Each extraction path 850 processes a different sideband within the electrical signal 150 to recover information signals 140A and 140B, respectively. As an example, extraction path 850A might process the upper sideband 154U; whereas extraction path 850B processes the lower sideband 154L. Both extraction paths 850 may use the same tone (e.g., the optical carrier) in their processing, or they may use different tones. Combiner 860 receives the recovered information signals 140A and 140B and constructively combines them to produce a resultant difference component 140C, which contains the original information signal. The difference components 140A and 140B typically may be phase shifted with respect to each other in order to align their phases before they are combined; the amount of the phase shift may be frequency-dependent. If difference components 140 are located at difference frequencies, combiner 860 may also frequency shift them to a common frequency before combining.

In a preferred embodiment, each path 850 is based on the approach of signal extractor 690 of FIG. 6, except that each extraction path 850 is designed to process a different sideband. Thus, for example, the bandpass filter 610 for extraction path 850A may be tuned to select the optical carrier and upper sideband 154U; whereas the bandpass filter 610 for extraction path

850B might select the optical carrier and lower sideband 154L. Alternately, each extraction path 850 may be based on the approach of signal extractor 790 of FIG. 7.

FIG. 9 is a block diagram of one embodiment 990 of signal extractor 890 in which the extraction paths 850 share components, although the sidebands are still processed separately. In this embodiment, each of the extraction paths 850 is based on signal extractor 790. Extraction path 850A processes the upper sideband 154U; whereas extraction path 850B processes the lower sideband 154L. Both extraction paths use the optical carrier as the tone 526. Hence, they may share a common bandpass filter 710, which selects the optical carrier. In other words, the extraction paths are overlapping. The tone 526 is then fed to both multipliers 720 in each respective extraction path 850.

Combiner 860 includes a phase shifting element 912 and an adder 914. Phase shifting element 912 phase shifts the difference component 140A produced by extraction path 850A so that it is in phase with the difference component 140B produced by extraction path 850B. Adder 914 then adds the two in-phase components to produce the resulting difference component 140C.

In FIGS. 3-9, the optical carrier played the function of the tone 146. FIG. 10 illustrates an example in which a tone 146 is located at a frequency other than the carrier frequency. In particular, FIG. 10 is a diagram of another embodiment 1010 of transmitter 100 using a pilot tone. Transmitter 1010 includes an optical source 112 coupled to an MZM 314 as in FIG. 3. However, transmitter 1010 also includes a combiner 1020 and a pilot tone generator 1030. The pilot tone generator 1030 is coupled to one input of combiner 1020, the output of which drives MZM 314. The other input of combiner 1020 receives information signal 140.

In transmitter 1010, combiner 1020 combines the pilot tone at a frequency $f_P$ with the incoming information signal 140 and uses the combined signal to modulate MZM 314. If MZM 314 is biased at the $V_\pi$ point, the resulting spectrum 1040 will include upper and lower sidebands 1044 of the information signal, upper and lower sidebands 1048 of the pilot tone, and no optical

carrier. Each sideband 1048 of the pilot tone may be used by signal extractor 190 as a tone 146. In other words, the signal extractor may mix one of the pilot tones 1048 with one of the sidebands 1044 to recover the information signal 140.

All of the signal extractors 190 described above may be adapted for use with optical signal 1040. For example, referring to FIG. 6, bandpass filter 610 may be adjusted to select one of the sidebands 1044 and one of the pilot tones 1048. The square law device 620 would then produce a corresponding difference component 672. Since this difference component might not lie exactly at baseband, low pass filter 630 may also need to be adjusted in order to recover the correct frequency components. Similarly, referring to FIG. 7, extractor 790 may be adapted for use with signal 1040 by similarly adjusting the frequency bands for filters 710, 712, and 730 to select an appropriate sideband 1044, pilot tone 1048 and difference component 772, respectively. Similar adjustments may be made to the systems discussed in FIGS. 8 and 9. Transmitter 1010 and optical signal 1040 are merely illustrative, other combinations of tones and sidebands will be apparent.

Although the invention has been described in considerable detail with reference to certain preferred embodiments thereof, other embodiments are possible. Therefore, the scope of the appended claims should not be limited to the description of the preferred embodiments contained herein.